

## Hot Gas in Planetary Nebulae

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**Abstract.** Diffuse X-ray emission has been detected in a small number of planetary nebulae (PNe), indicating the existence of shocked fast stellar winds and providing support for the interacting-stellar-winds formation scenario of PNe. However, the observed X-ray luminosities are much lower than expected, similar to the situation seen in bubbles or superbubbles blown by massive stars. Ad hoc assumptions have been made to reconcile the discrepancy between observations and theoretical expectations. We have initiated *FUSE* programs to observe O VI absorption and emission from PNe, and our preliminary results indicate that O VI emission provides an effective diagnostic for hot gas in PN interiors.

### 1. Introduction

The formation of planetary nebulae (PNe) is a complex issue. The current fast stellar wind from the central star of a PN must interact with the previous slow AGB wind; it has thus been suggested that PNe are formed by interacting stellar winds (Kwok, Purton, & Fitzgerald 1978). The frequently observed multipolar and point-symmetric structures of young PNe suggest that collimated outflows are responsible for shaping PNe in early evolutionary stages (Sahai & Trauger 1998). The fast stellar winds and high-velocity collimated outflows, upon impacting the ambient medium, will be shocked to a temperature of  $T = (3/16)\mu v^2/k$ , where  $\mu$  is the average mass per particle,  $v$  is the shock velocity, and  $k$  is the Boltzmann constant. Hot gas at X-ray-emitting temperatures, i.e.,  $\geq 1 \times 10^6$  K, can be generated for shock velocities greater than  $\sim 300$  km s $^{-1}$ .

As reviewed by Guerrero et al. (in this volume), X-ray observations have revealed hot gas in a number of young PNe such as NGC 6543 and NGC 7027, and established stringent upper limits on the hot gas content in evolved PNe such as NGC 7293 (the Helix). The detection of diffuse X-ray emission from PNe provides a strong support for the interacting-stellar-winds scenario of PN formation. This formation mechanism is in fact similar to that for circumstellar bubbles blown by Wolf-Rayet (WR) stars. Massive WR stars are descendants of red supergiants or luminous blue variables which lose mass via copious slow winds; the fast WR wind sweeps up the previous slow wind and forms a circumstellar bubble. Comparisons between PNe and WR bubbles will help us understand both types of objects. In the first part of this paper, we will discuss the physical properties of the  $10^6$  K hot gas in PN interiors and make comparisons with shocked stellar winds in WR bubbles.

In the second part of this paper, we will discuss hot gas at cooler temperatures, i.e., a few  $\times 10^5$  K, in order to: (1) determine whether some evolved PNe are filled with such cooler hot gas, and (2) study the interface layer between the  $10^6$  K interior gas and the  $10^4$  K nebular shell in young PNe. We will present far-UV observations of the  $10^5$  K gas in PNe and use the results to make predictions about the presence or absence of  $10^6$  K hot gas in PN interiors.

## 2. $10^6$ K Hot Gas

*Chandra* and *XMM-Newton* observations of diffuse X-ray emission from PNe allow us to examine the spatial distribution and temperatures of the hot gas. Among the six PNe with diffuse X-ray emission, Mz 3 and NGC 6543 are the only two that are adequately resolved by the instrumental point spread function, and both of them show a limb-brightened X-ray morphology, indicating that the dense X-ray-emitting gas is concentrated near the inner walls of their nebular shells. This is similar to what we have observed in the WR bubbles NGC 6888 and S 308 (Chu et al. 2003; Gruendl et al. 2004); see Fig. 1 for an *XMM-Newton* EPIC image of S 308 and a comparison with an optical image. The large angular size of S 308 makes it possible to see the detailed relationship between the hot interior gas and the cooler nebular shell.

X-ray spectra of the hot gas in PN interiors (Guerrero et al. in this volume) show a narrow range of temperatures,  $2 - 3 \times 10^6$  K. These temperatures are much lower than the  $\sim 10^7$  K gas detected in superbubbles around young clusters, where colliding stellar winds may have produced the hot gas and the high temperatures (Townsley et al. 2003). On the other hand, the temperatures of the X-ray-emitting gas in PNe are similar to the  $1 - 2 \times 10^6$  K gas detected in the WR bubbles NGC 6888 and S 308 (see their spectra in Fig. 1).

Both PNe and WR bubbles have been modeled hydrodynamically (Zhekov & Perinotto 1996, 1998; García-Segura et al. 1996a,b), assuming that the fast stellar wind is shock-heated to high temperatures and forms a contact discontinuity with the photoionized  $10^4$  K nebular shell. It is further assumed that thermal conduction and mass evaporation take place at the hot/cold gas inter-

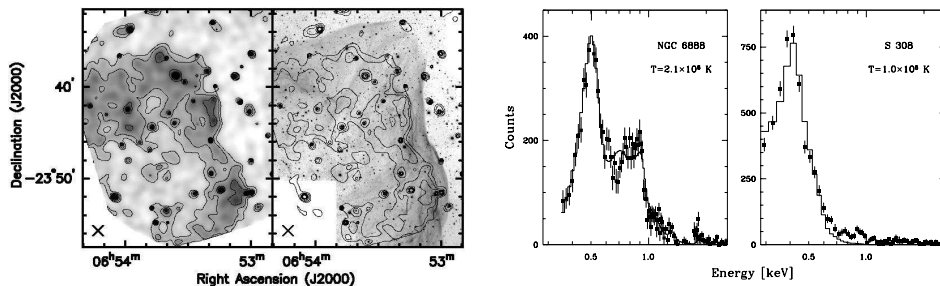


Figure 1. *Left:* *XMM-Newton* EPIC image of the NW quadrant of the WR bubble S 308, and an [O III]  $\lambda 5007$  line image overlaid with X-ray contours. The location of the central WR star is marked with an “x”. *Right:* *Chandra* ACIS-S spectrum of the hot gas in NGC 6888 and *XMM-Newton* EPIC/pn spectrum of the hot gas in S 308.

face, which lowers the temperature and raises the density of the hot interior gas. In fact, the hot interior gas is dominated by the evaporated nebular material.

As the X-ray emission is proportional to the square of the density, the integrated X-ray spectrum of the hot gas will be dominated by the emission from the densest gas which is at the lowest temperatures. Therefore, the low temperatures derived from model fits to the X-ray spectra are expected. The X-ray luminosities of the diffuse emission from PNe and WR bubbles are, however, at least an order of magnitude lower than those expected from models (Chu et al. 2001; Wrigge et al. 1994), implying that the amount of hot gas is significantly less than that predicted by models with thermal conduction.

Several possibilities have been suggested to reconcile the discrepancies between observation and theory (Arnaud et al. 1996; Soker & Kastner 2003): (1) the fast stellar wind may have evolved with time, with a lower velocity or mass loss rate in the past; (2) the fast stellar wind is anisotropic, with a bipolar structure; and (3) the thermal conduction at the hot/cold gas interface may be inhibited by the presence of magnetic fields. Unfortunately, diffuse X-ray emission has been detected in only six PN interiors; two PNe are not adequately resolved spatially, and another two are detected with less than 100 counts. The current X-ray observations are clearly inadequate to constrain models and to discern the above possibilities. High-quality X-ray observations of PNe are badly needed.

### 3. $10^5$ K Hot Gas

Hot gas at  $10^5$  K is traditionally studied with spectral lines of highly ionized species, such as CIV, NV, and OVI. If these ions are produced by thermal collisions, CIV, NV, and OVI will be the dominant ionization stages for C, N, and O at temperatures of  $1 \times 10^5$ ,  $2 \times 10^5$ , and  $3 \times 10^5$  K, respectively. As the ionization potentials of CIII, NIV, and OV are 47.9, 77.5, and 113.9 eV, photoionization of these ions becomes significant in PNe with central stars at stellar effective temperatures greater than  $\sim 35,000$ , 75,000, and 125,000 K, respectively. Therefore, OVI provides the best diagnostic for  $10^5$  K gas, as it is the least easily confused by photoionization.

The OVI  $\lambda\lambda 1032, 1037$  lines can be observed with the recently launched *Far Ultraviolet Spectroscopic Explorer (FUSE)*. Four *FUSE* observing programs were carried out to search for  $10^5$  K gas in PN interiors. Some observations use spectra of the central stars to search for nebular OVI absorption, while others use spectra of the nebula (avoiding the central star) to search for OVI emission. These four programs are:

- OVI absorption observation of 10 PNe (PI: Gruendl; AO2)
- OVI emission observation of NGC 6543 (PI: Guerrero; AO3)
- OVI emission observation of NGC 7009 (PI: Iping; AO3)
- OVI emission observation of 9 PNe (PI: Guerrero; AO4)

These observations have produced many exciting results. First of all, *FUSE* observations detected OVI in NGC 6543 and NGC 7009, two PNe with known diffuse X-ray emission. The top panels of Fig. 2 display *FUSE* spectra of their central stars; both show pronounced P Cygni profiles in the stellar OVI lines, indicating the presence of fast stellar wind. NGC 6543 shows a stellar spectrum with nebular OVI absorption at a velocity blue-shifted from the nebular sys-

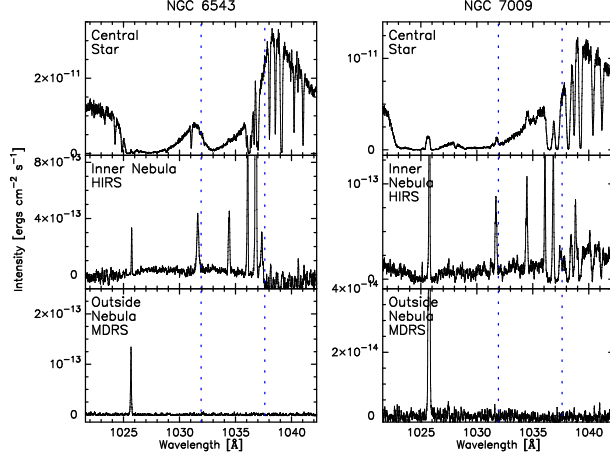


Figure 2. *FUSE* spectra of NGC 6543 and NGC 7009, two PNe with known diffuse X-ray emission. The vertical dashed lines mark the positions of the O VI lines. See text for more descriptions.

temic velocity, indicating that it is associated with the interface layer on the approaching side of the nebular shell. NGC 7009 does not show obvious nebular O VI absorption in its stellar spectrum. The middle panels of Fig. 2 display *FUSE* spectra of apertures centered inside the nebulae. Both nebulae show obvious O VI emission lines. The bottom panels of Fig. 2 display *FUSE* spectra of apertures centered outside the nebulae, where only airglow lines are seen. *FUSE* observations of NGC 6543 and NGC 7009 demonstrate clearly that the O VI emission from interfaces between the  $10^6$  K interior and the  $10^4$  K nebular shell can be detected. Quantitative analysis of the O VI emission and absorption lines, complicated by the interstellar and circumstellar  $H_2$  absorption along the line of sight, is in progress.

*FUSE* observations of the Helix Nebula (Fig. 3), a PN confirmed to lack  $10^6$  K gas, show contrasting spectra in both the central star and the nebula. The spectrum of the central star shows stellar O VI absorption, but not P Cygni profiles, indicating a lack of fast stellar wind, which is consistent with the conclusion derived from *IUE* observations (Cerruti-Sola & Perinotto 1985). Neither O VI absorption nor O VI emission from the nebula is detected. It is thus reasonable to expect that a lack of both stellar P Cygni profile in O VI and nebular O VI is a good indication of an absence of hot gas in the PN interior. NGC 3132 is an awarded *Chandra* target in Cycle 5. The *FUSE* observations of its central star and the nebula, displayed in Fig. 3, show neither stellar P Cygni O VI nor nebular O VI. We predict that no  $10^6$  K hot gas exists in NGC 3132 and that *Chandra* observations of NGC 3132 will not detect any diffuse X-ray emission.

#### 4. Future Work

X-ray observations have shown that hot gas exists in some PN interiors, and this interior hot gas may play an important role in the formation and evolution of PNe. To understand the interacting stellar winds in PNe, high S/N and high spa-

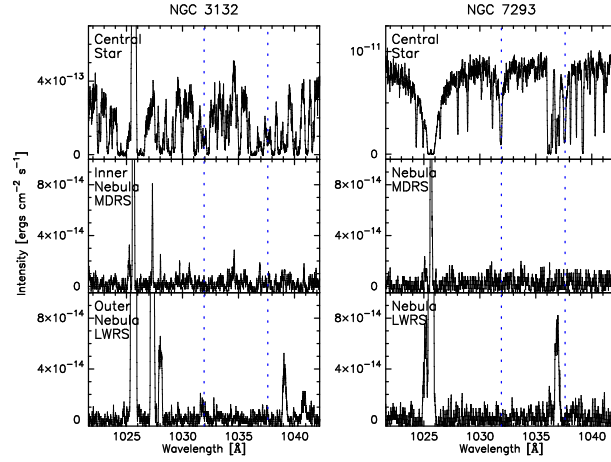


Figure 3. *FUSE* spectra of NGC 3132 and NGC 7293. Note the contrasting stellar and nebular O VI lines between these spectra and those in Fig. 2. The vertical dashed lines mark the positions of the O VI lines. See text for more descriptions.

tial resolution X-ray observations of more PNe are needed. *FUSE* observations of O VI emission offer an effective diagnostic for the presence of hot gas in PNe, and should be used to guide the target selection for X-ray observations. Future models of interacting stellar winds need to consider the plasma micro-physics and dynamical mixing of nebular material, in addition to a critical assessment of the degree of thermal conduction. When high-quality X-ray spectra are available, they need to be modeled with considerations of non-equilibrium ionization and temperature structure in the hot gas.

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